



Auxiliary health diagnosis method for lead-acid battery

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ABSTRACT

This paper proposes a health auxiliary diagnosis method for the lead-acid battery unit. The proposed method is based on Approximate Entropy (ApEn). Since ApEn can quantify the regularity of a data sequence and the discharging curve for a health lead-acid battery unit is smooth, the proposed method can detect the degradation of battery unit caused by the internal short, opening of internal shorted or cell undergoing reversal using the distorted discharging curve. Aging experiments for the lead-acid battery are developed to verify the proposed method. The experimental results verify that the proposed health auxiliary diagnosis method can diagnosis the degradation of battery unit caused by the internal short, opening of internal shorted or cell undergoing reversal.

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1. Introduction

Lead-acid batteries have been widely used in electric vehicles [1], photovoltaic system [2,3] and PV/wind hybrid energy conversion system [4–7]. State-of-health (SOH) indicates the ability of the battery to perform well during charging and discharging period. SOH of the battery is used to supply the degradation information of battery to the users. The battery degradation may be caused by drying out, grid corrosion, thermal runaway, electrolyte leakage, internal shorts [8] or opening of internal shorted cell. Several methods have already been developed to estimate the SOH of a battery.

Capacity and coulomb counting method is the most popular method to indicate the SOH [9,10]. The “coup de fouet” method involves measuring the trough voltage (low voltage point) in the “coup de fouet” region and uses it to determine the SOH of a battery [11]. Internal impedance is also claimed to measure the SOH of batteries [12], and it can also be incorporated to the fuzzy logic data analysis to estimate the SOH of the battery [13,14].

The authors ever proposed the Approximate Entropy method and the Sample Entropy method to predict the aging of the lead-acid battery [15,16]. The accuracy of the Approximate Entropy method seems to be better than that of the Sample Entropy although the calculation loading of the Sample Entropy is less than that of the Approximate Entropy. The authors also ever used the

Sample Entropy method to diagnosis the SOH of the lead-acid battery [17]. Nevertheless, the Approximate Entropy method still has not been used to diagnosis the SOH of the lead-acid battery.

In this paper, a novel health auxiliary diagnosis method based on Approximate Entropy (ApEn) is proposed to detect the degradation of lead-acid battery unit caused by the internal shorts or opening of internal shorted. The advantage of the proposed method is that the state-of-charge (SOH) of the lead-acid battery unit is estimated automatically at the end of each discharging cycle by measuring the battery voltage and current of a battery unit, so that no complicated measurement is required. To verify the performance of proposed auxiliary SOH diagnosis method, aging experiments of lead-acid battery are developed.

2. Approximate Entropy and health auxiliary diagnosis method

ApEn was developed for measuring a complex system [18] and has been applied to Classify Ventricular Tachycardia and Fibrillation [19,20]. The algorithm for computing $ApEn(r, m, N)$ has been published elsewhere [18]. For a data sequence $x(n) = x(1), x(2), x(3), \dots, x(N)$, where N is the total number of data points to calculate $ApEn(r, m, N)$, a run length m and a tolerance window r must be specified to compute $ApEn(r, m, N)$. In order to use fewer data points to measure the change in a complex system, the parameter m used in this paper is 2 [18]. Normally, tolerance window, r , is 0.2 times the standard deviation (SD) of the original data [18]. SD can be represented as:

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$$SD = \sqrt{\frac{1}{N-1} \sum_{n=1}^N \left[x(n) - \frac{1}{N} \sum_{n=1}^N x(n) \right]^2} \quad (1)$$

ApEn algorithm [18,21] can be summarized as follows:

(1) Form m -vectors, $X(1)$ to $X(N-m+1)$ defined by:

$$X(i) = [x(i), x(i+1), \dots, x(i+m-1)] \quad i = 1 \text{ to } N-m+1 \quad (2)$$

$$X(j) = [x(j), x(j+1), \dots, x(j+m-1)] \quad j = 1 \text{ to } N-m+1 \quad (3)$$

(2) Defining the distance $d[X(i), X(j)]$ between vectors $X(i)$ and $X(j)$ as the maximum absolute difference between their respective scalar components:

$$d[X(i), X(j)] = \max[|x(i+k) - x(j+k)|] \quad k = 0 \text{ to } m-1 \quad (4)$$

The relation matrix is show as:

	$x(j) \rightarrow x(1)$	$x(2)$	$x(N-m)$	$x(N-m+1)$
$x(1)$	$d(1,1)$	$d(1,2)$	$\dots d(1,N-m)$	$d(1,N-m+1)$
$x(2)$	$d(2,2)$	$d(2,2)$	$\dots d(2,N-m)$	$d(2,N-m+1)$
$\dots$	$\dots$	$\dots$	$\dots$	$\dots$
$\dots$	$x(i)$	$\dots$	$\dots$	$\dots$
$\dots$	$\downarrow$	$\dots$	$\dots$	$\dots$
$\dots$	$\dots$	$\dots$	$\dots$	$\dots$
$x(N-m)$	$d(N-m,1)$	$d(N-m,2)$	$d(N-m,N-m)$	$d(N-m,N-m+1)$
$x(N-m+1)$	$d(N-m+1,1)$	$d(N-m,2)$	$\dots d(N-m+1,N-m)$	$d(N-m+1,N-m+1)$

(3) Defining for each i , for $i = 1$ to $N-m+1$, let

$$C_r^m(i) = V^m(i)/(N-m+1) \quad (5)$$

where $V^m(i) = \text{No. of } d[X(i), X(j)] \leq r$

Taking the natural logarithm of each C_r^m , and averaging it over i as defined in step (3):

$$\phi^m(r) = \frac{1}{N-m+1} \sum_{i=1}^{N-m+1} \ln(C_r^m(i)) \quad (6)$$

(4) Increase the dimension to $m+1$ and repeat steps (1)–(4),

(5) Calculate ApEn value for a finite data length of N :

$$\text{ApEn}(m, r, N) = \phi^m(r) - \phi^{m+1}(r) \quad (7)$$

The ApEn is proportional to the variation rates and variation amount of data sequence. This means that the ApEn value of variable data sequence is enlarged significantly than that of the smooth data sequence. The discharging voltage will be decreased smoothly and the value of ApEn will be approached to zero for a healthy battery. The degraded battery cells may result in internal shorts [8,22], opening of internal shorted or cell undergoing reversal [23]. When a cell is shorted or undergoes reversal, it will result in an abrupt voltage drop of a battery unit [22]. If an internally shorted is opened, it will result in an abrupt voltage rise of a battery unit. Hence, the degradation of battery caused by internal shorts, opening of internal shorted or undergoing cell reversal will

distort the discharging curve of a battery unit. At the same time, the relative value of ApEn will also be changed. The proposed method is based on the concept that the above battery degradation phenomena will result in an abrupt change in the discharging voltage and ApEn. However, the battery current variation caused by the abrupt change of load will also result in abrupt change of discharging voltage. To avoid the un-corrected diagnosis caused by the abrupt change of discharging voltage, the development of a diagnosis method which can neglect the curves of discharging voltage distortion caused by the abrupt change of normal discharging current is necessary. The proposed method cannot diagnose the degraded battery phenomena, such as dry out or grid corrosion, and it is only an auxiliary diagnosis method for the SOH of the battery (ADSOH).

The defined ADSOH can be summarized as follows:

- (1) calculating the value of current ApEn by ApEn algorithm;
- (2) calculating the value of voltage ApEn by ApEn algorithm;
- (3) comparing the value of current ApEn and the value of voltage ApEn;

- (4) the value of voltage ApEn should be checked at the same time if the value of current ApEn is larger than the set value (0.01 is defined), and then the value of ADSOH is defined as zero if both values of current ApEn and voltage ApEn are larger than the setting values;
- (5) the value of ADSOH will be defined to be equal to the value of voltage ApEn except the condition in step 4;
- (6) if the value of ADSOH in whole curve is zero and the SOH of the battery can be determined healthy. If the ADSOH curve shows serious fluctuations and the SOH of the battery can be determined degradation.

Fig. 1 shows the flowchart of the proposed SOH diagnosis method for a battery unit. Normally, measuring devices are employed to measure and retrieve the data of voltages and currents for a battery. During the charging and discharging period, ApEn of voltage and current will be calculated. In order to avoid the effect of normal discharging current variation in determining the battery health status, the ApEn of voltage and current was compared, so that the SOH of battery can be diagnosed correctly. This means that the proposed SOH diagnosis method can avoid the effect of abrupt voltage drop or rising due to the sudden variation of normal discharging current.

If the degradation of a battery unit is caused by internal shorts, opening of internal shorted or cell undergoing reversal, the battery voltage will vary immediately. At the same time, the value of ADSOH will be fluctuated evidently; so that the value of ADSOH can be converted into a SOH index to indicate the health status of battery.

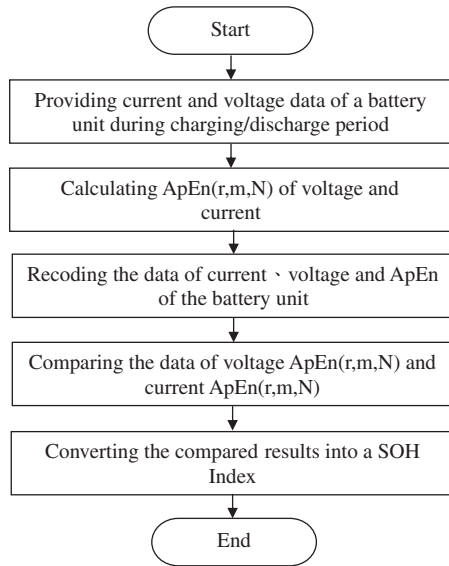


Fig. 1. Flow chart of the proposed SOH diagnosis method for a battery unit.

3. Experimental system

The accelerated battery aging experiments developed to evaluate the charging and discharging characteristics of the lead-acid battery [24] are used to verify the proposed auxiliary SOH diagnosis method. Fig. 2 shows the experimental system. The experimental system includes a battery charger, a thermostat, several electromagnetic contactor (MC) switches, and a battery measure system (BMS).

The conditions for accelerated battery aging experiments are defined as follows:

- (1) Four independent strings of batteries are used in the experiments, and each string of batteries consisted of eight 7-Ah 12-V VRLA battery units connected in series. Each battery unit consists of six cells connected in series internally.
- (2) The ambient temperature was kept at 50 °C.
- (3) Sample data per 10 s was retrieved upon discharging the battery.
- (4) Sample data was retrieved every 5 min when the battery was charged.
- (5) The final discharging voltage for each string of batteries was 76.8 V.
- (6) The discharging load for each battery set was a Halogen Lamp (120 V 500 W * 3).
- (7) The experiment stops as the capacity of each string of batteries was decreased to 60% of the initial capacity.

4. Experimental results

Fig. 3 shows the charging/discharging current and the relative ApEn for the battery (string 1, No. 3) at the 5th charging/discharging cycle under different r . In Fig. 3a, the positive value represents the discharging current, and the negative value represents the charging current. As seen in Fig. 3b and c, the results of ApEn that r is the recommended value of $0.2 * SD$ in Fig. 3b are more irregular than the results that r is defined as a constant value 0.4 in Fig. 3c. The nominal voltage of lead-acid battery per-cell is about 2 V. When a cell short occurs and the discharge current remains the same (the load is not changed), the maximum voltage drop is a cell voltage of battery (about 2 V). Loss of active material results in too

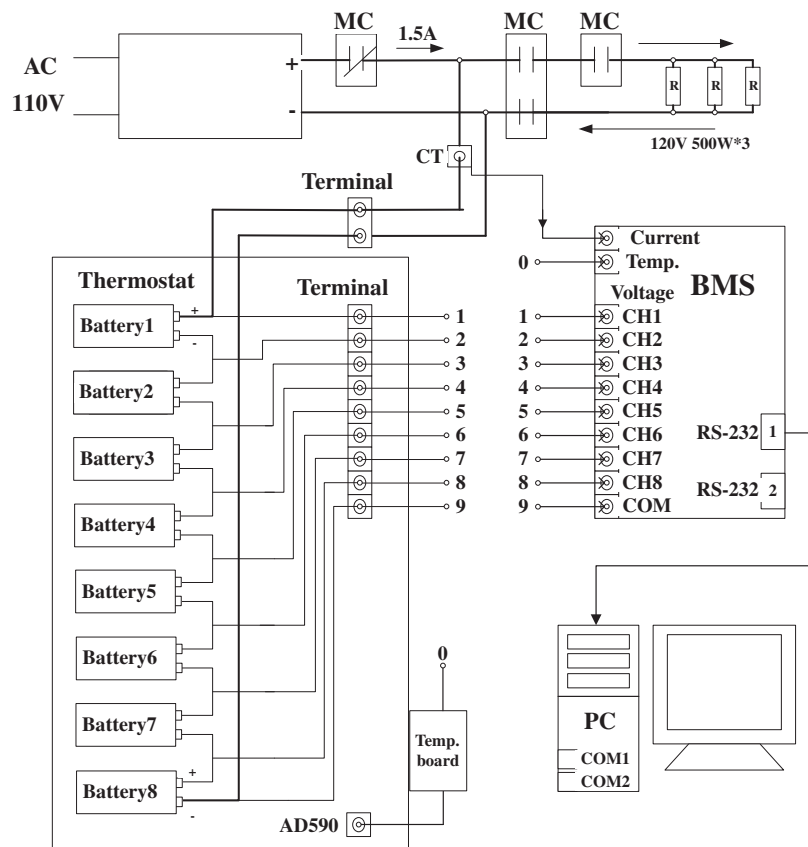


Fig. 2. Experimental system for a string of batteries.

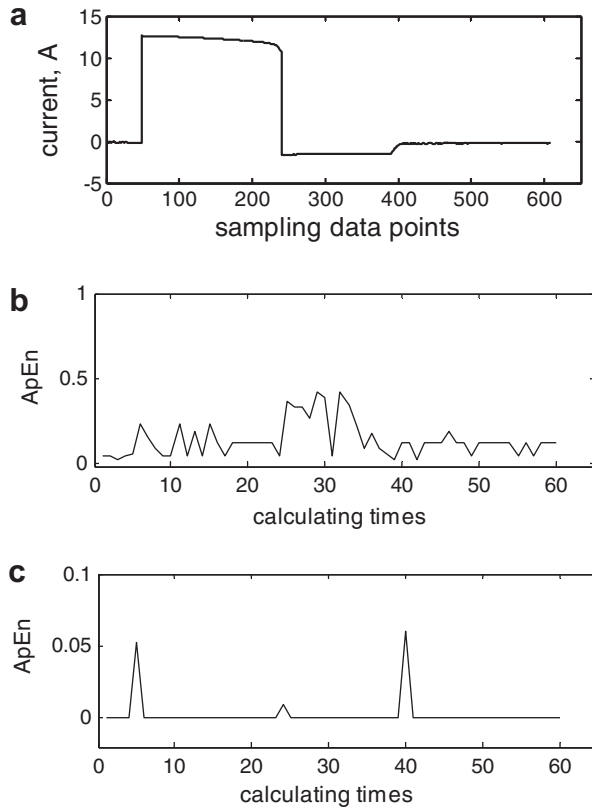


Fig. 3. Experimental results of the battery (string 1, No. 3) at 5th charging/discharging cycle (a) charging/discharging current, (b) ApEn ($r = 0.2 * SD$, $m = 2$, $N = 10$), and (c) ApEn ($r = 0.4$, $m = 2$, $N = 10$).

much sediment [25], and dendrite outgrowths from the electrode [26] can result in cell short. The voltage drop caused by cell short is more serious than that caused by the normal discharge. When one of the plates (such as the negative plate) is weak, it will result in a sharp voltage drop of about 1 V [22]. If one of the plates not serious short, the resulted sharp voltage drop is below 1 V. In general, r is essentially a filter where the characteristic of filter depends on the choice of r . For example, a large r can be regarded as an all-pass filter since the number of self-matches will be large, whereas a small r can lead to a low-pass filter like behavior since it will lead to few self-matches and detailed information may be lost [27]. Therefore, the value of r must smaller than 1. Fig. 4 shows the charging/discharging voltage and the relative ApEn for the battery (string 1, No. 3) at the 5th charging/discharging cycle under different r . In Fig. 4a the voltage of a complete charging/discharging cycle. Fig. 4b–f shows the results of ApEn when the r value is chosen as 0.1, 0.2, 0.3, 0.4 and 0.5 respectively. As seen Fig. 4b and c, the results of ApEn are irregular when the r value is small (0.1 in Fig. 4b and 0.2 in Fig. 4c). In the other hand, the results of ApEn shown in Fig. 4f cannot effectively respond the variation of the battery voltage in Fig. 4a when the r value is high (0.5 in Fig. 4a). As seen Fig. 4c and d in the results of ApEn can respond the variation of the battery voltage in Fig. 4a effectively. The total measured experimental data points during a charging/discharging period is 650 points. A huge computing resource will be used for calculating ApEn while the parameter N is large, and the calculated result may be inaccurate when the parameter N is small [28]. The parameter N used in the following experiments is 10. Hence, the parameters r , m and N of ApEn used in the following experiments are 0.4, 2 and 10, respectively.

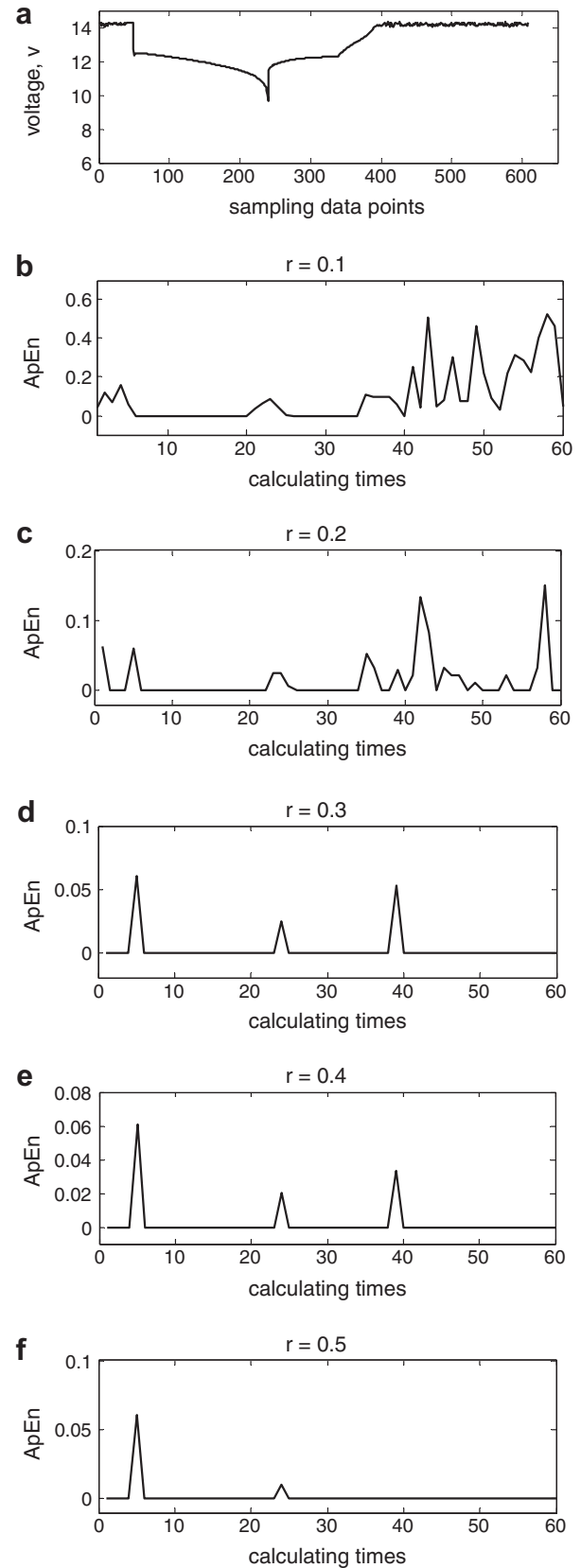


Fig. 4. Experimental results of the battery (string 1, No. 3) at 5th charging/discharging cycle (a) charging/discharging voltage, (b) ApEn ($r = 0.1$, $m = 2$, $N = 10$), (c) ApEn ($r = 0.2$, $m = 2$, $N = 10$), (d) ApEn ($r = 0.3$, $m = 2$, $N = 10$), (e) ApEn ($r = 0.4$, $m = 2$, $N = 10$), and (f) ApEn ($r = 0.5$, $m = 2$, $N = 10$).

Fig. 5 shows the curves for the battery current and the battery voltage (string 1, No. 3) and their calculated ApEn ($r = 0.4$, $m = 2$, $N = 10$) at the 5th charging/discharging cycle. The operation modes for the battery charger include the constant current mode and the constant voltage mode, to charge the batteries, and the load used for discharging is a constant resistor. Consequently, the curves of current and voltage are smooth except when the battery is changed from charging status to discharging status, and from discharging status to charging status and from constant current charging to constant voltage charging. The calculated ApEn is nearly zero except at the points under the transition of charging/discharging status and different charging modes. If the value of current ApEn in

Fig. 5b is larger than the set value (0.01 is defined), the value of voltage ApEn in Fig. 5d should be checked at the same time. If both values of current ApEn and voltage ApEn are larger than the setting values, the value of ADSOH is defined as zero. This means that the battery is “healthy”. If only the value of voltage ApEn is larger than the setting value, the value of ADSOH will be defined to be equal to the value of voltage ApEn. This means that the battery is “degrading”. As seen in Fig. 5e, the value of ADSOH is zero and the SOH of the battery can be determined “healthy”, and there is no need to change the battery.

Fig. 6 shows the current and voltage curves of battery in string 1, No. 3 and their calculated ApEn ($r = 0.4$, $m = 2$, $N = 10$) at the

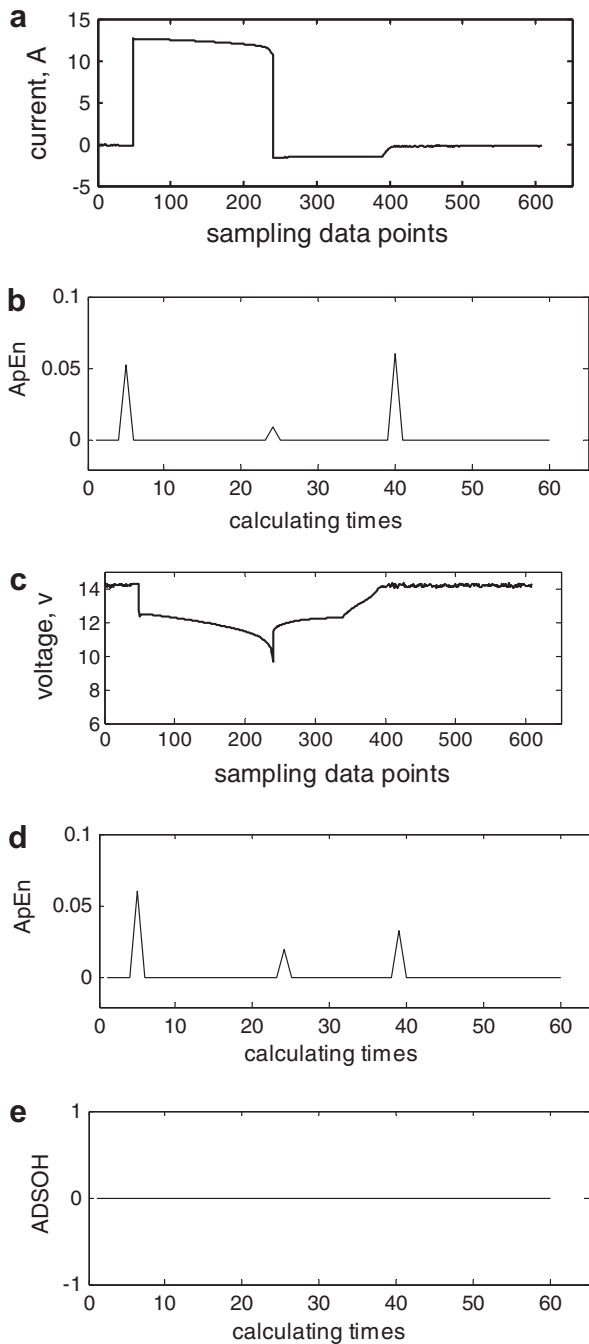


Fig. 5. Experimental results of the battery (string 1, No. 3) at 5th charging/discharging cycle, (a) charging/discharging current, (b) ApEn value of current, (c) charging/discharging voltage, (d) ApEn value of voltage, and (e) ADSOH.

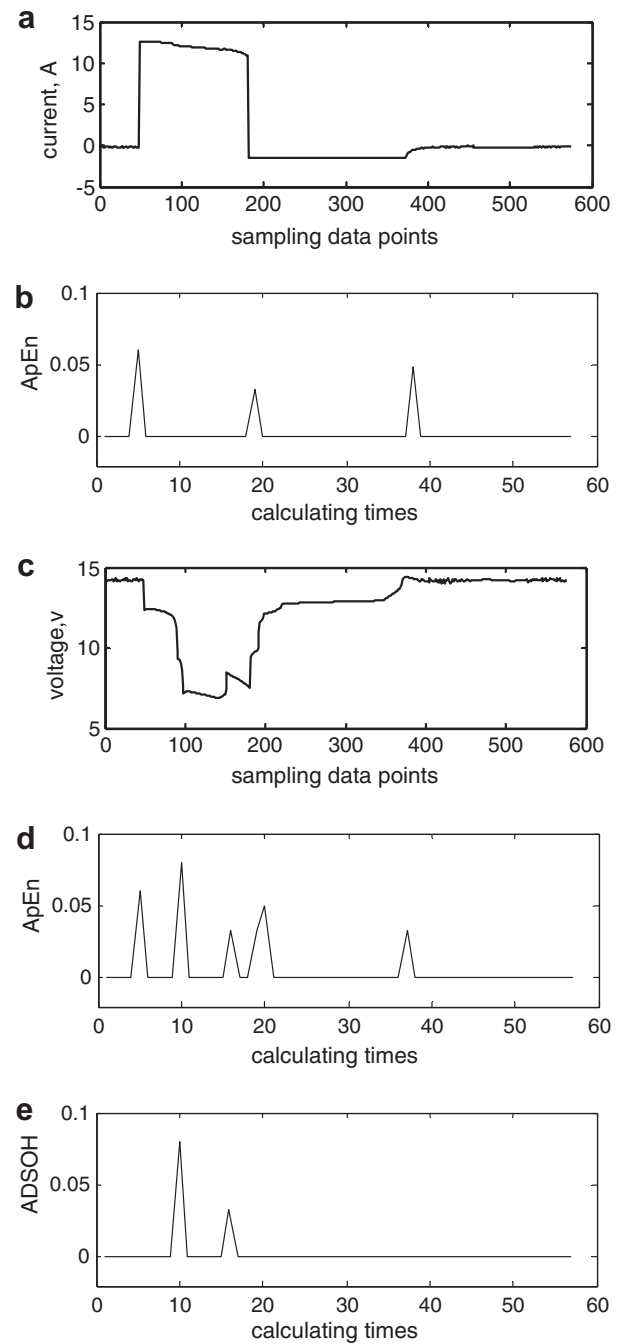


Fig. 6. Experimental results of the battery (string 1, No. 3) at 159th charging/discharging cycle, (a) charging/discharging current, (b) ApEn value of current, (c) charging/discharging voltage, (d) ApEn value of voltage, and (e) ADSOH.

159th charging/discharging cycle. As seen in Fig. 6a, the current curve is smooth except when the battery is changed from charging status to discharging status, from discharging status to charging status and from constant current charging to constant voltage charging. As seen in Fig. 6c, the voltage curve is still abnormal when the battery is changed from charging status to discharging status, from discharging status to charging status and from constant current mode to constant voltage mode. Besides, some additional unexpected variations distort the curve seriously during the discharging status. The abrupt drop of battery voltage close to the 91 and 98 sampling data points can be explained based on the fact that some cells in the battery are shorted, and the abrupt rise of

battery voltage close to the 152 sampling data point can be explained based on the fact that a shorted cell in the battery is opened. Comparing ApEn in Fig. 6b with Fig. 6d, the ADSOH results are shown in Fig. 6e. The ADSOH curve shows serious fluctuations, indicating degradation in the SOH of the battery.

Figs. 7 and 8 show the current, voltage, calculated ApEn ($r = 0.4$, $m = 2$, $N = 10$) and ADSOH curves of the battery in No. 1 of string 2, and Figs. 9 and 10 show the current, voltage, calculated ApEn ($r = 0.4$, $m = 2$, $N = 10$) and ADSOH curves of the battery in No. 4 of string 3. As seen in these figures, the curves of these two batteries are similar to the curves of battery in No. 3 of string 1. Hence, the proposed auxiliary diagnosis method based on ApEn for SOH

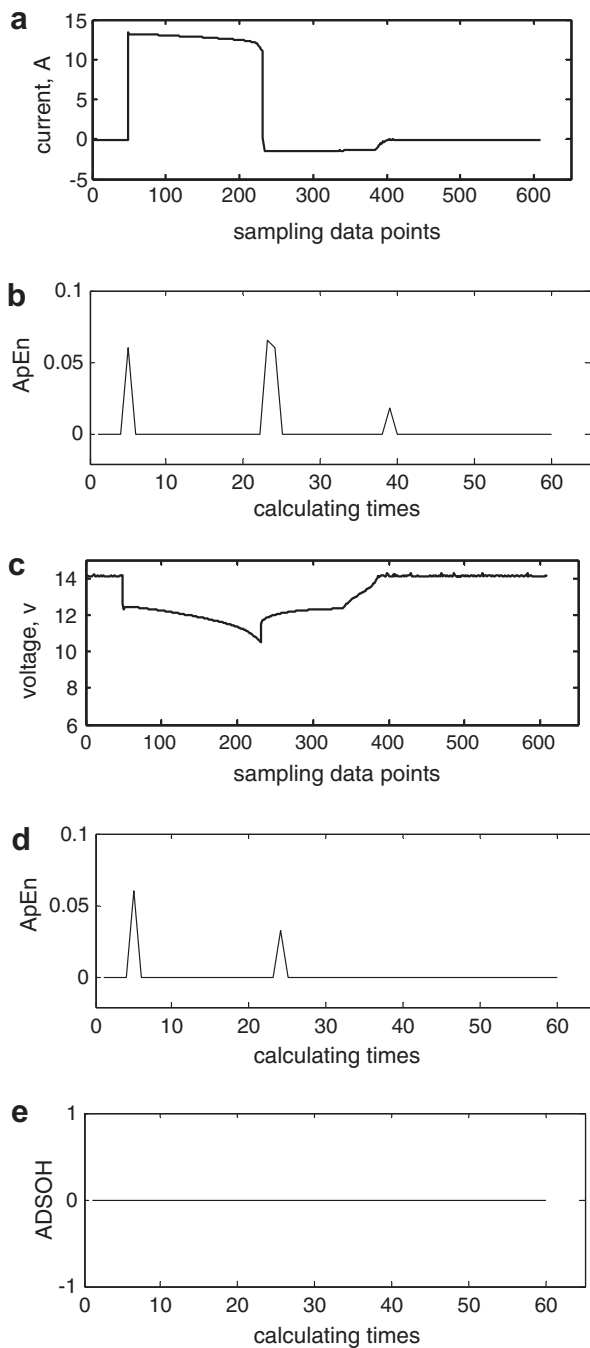


Fig. 7. Experimental results of the battery (string 2, No. 1) at 5th charging/discharging cycle, (a) charging/discharging current, (b) ApEn value of current, (c) charging/discharging voltage, (d) ApEn value of voltage, and (e) ADSOH.

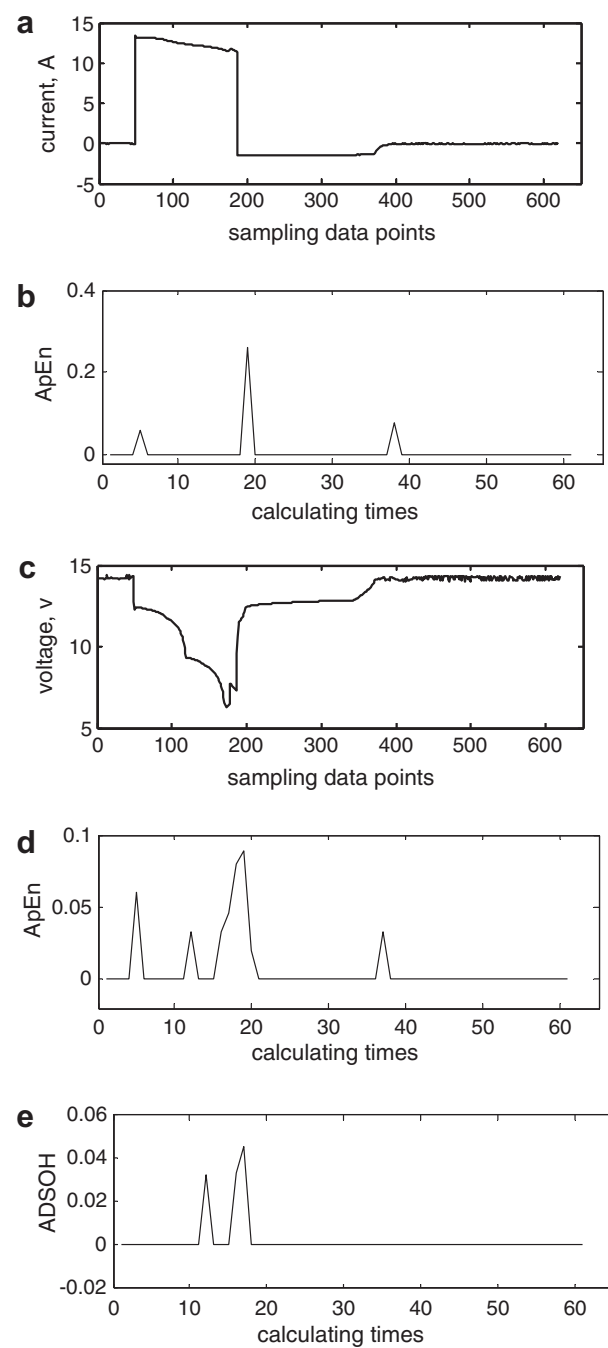


Fig. 8. Experimental results of the battery voltage (string 2, No. 1) at 107th charging/discharging cycle, (a) charging/discharging current, (b) ApEn value of current, (c) charging/discharging voltage, (d) ApEn value of voltage, and (e) ADSOH.

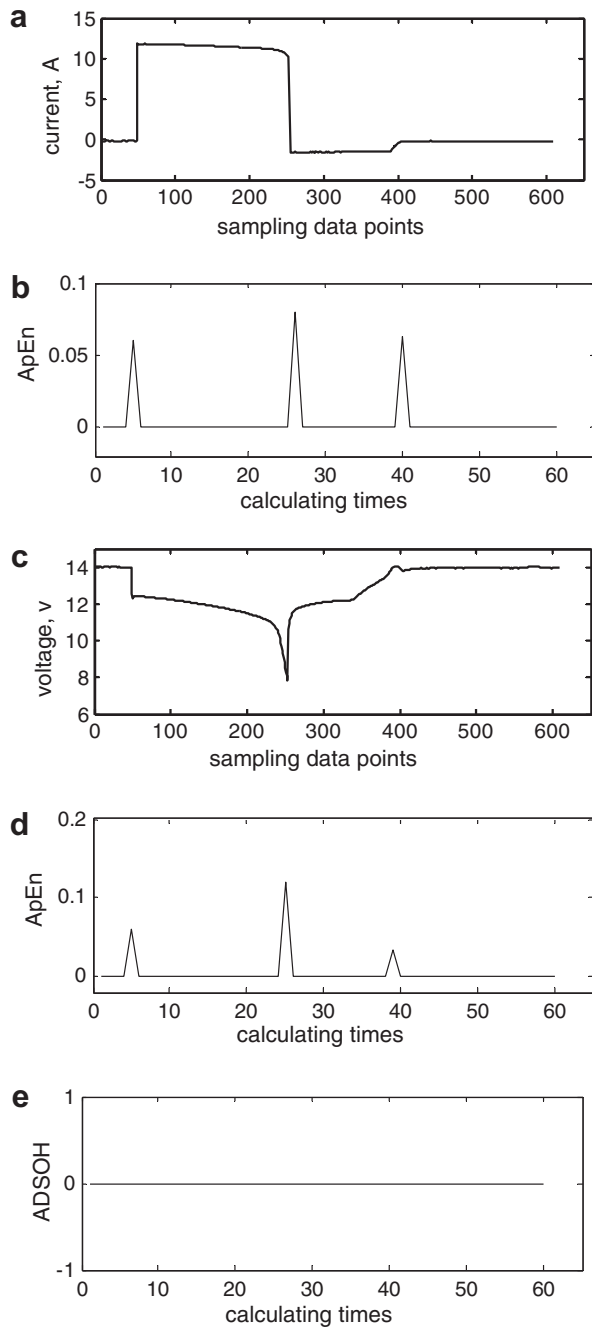


Fig. 9. Experimental results of the battery (string 3, No. 4) at 5th charging/discharging cycle, (a) charging/discharging current, (b) ApEn value of current, (c) charging/discharging voltage, (d) ApEn value of voltage, and (e) ADSOH.

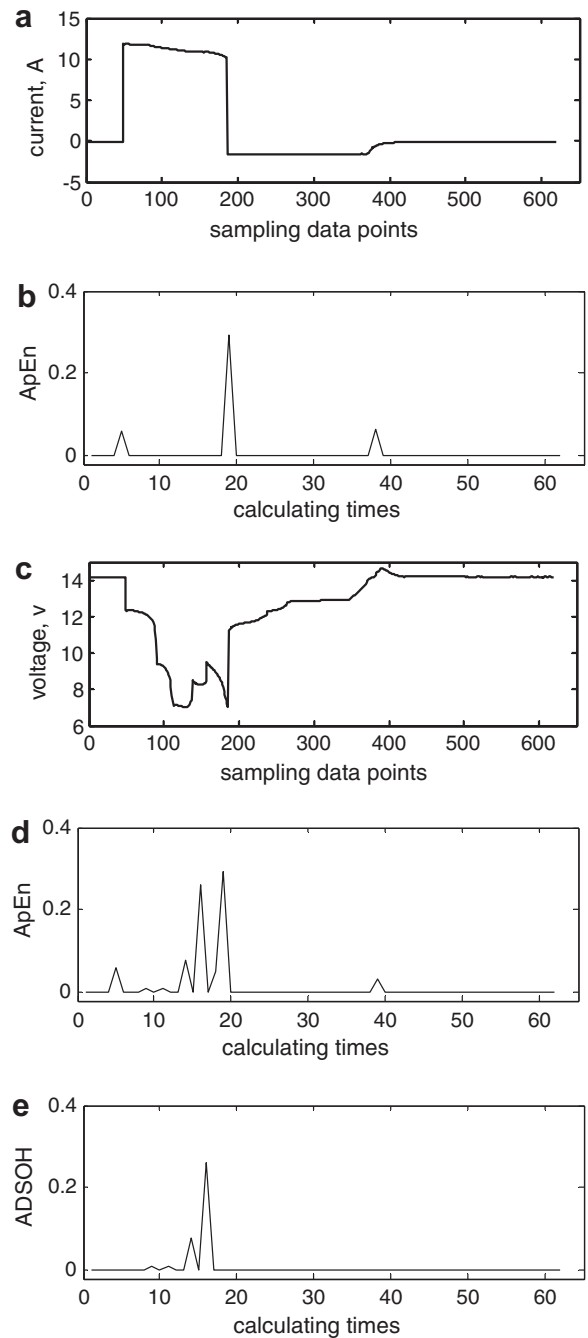


Fig. 10. Experimental results of the battery (string 3, No. 4) at 145th charging/discharging cycle, (a) charging/discharging current, (b) ApEn value of current, (c) charging/discharging voltage, (d) ApEn value of voltage, and (e) ADSOH.

can diagnose effectively the degradation of battery unit caused by the internal shorts or opening of internal shorted in the discharging process.

From the above, it can conclude that the ADSOH data can be used to determine the SOH of the battery and can avoid the uncorrected diagnosis caused by abrupt change in the discharging current. The authors ever used the Sample Entropy to serve as an indicator to diagnosis SOH of the lead-acid battery [17]. However, the proposed auxiliary diagnosis method based on ApEn for SOH is more evident than that based on SampEn although the Sample Entropy (SampEn) algorithm is simpler than the ApEn algorithm.

5. Conclusions

This paper proposes a novel auxiliary diagnosis method based on ApEn for SOH of a lead-acid battery unit. In this method, ADSOH is used to diagnose and indicate the degradation of the lead-acid battery unit caused by the internal short, opening of internal shorted or cell undergoing reversal. The proposed method has the advantage that the SOH of a battery is estimated automatically at the end of each discharging cycle by measuring the battery voltage and current, so that the complicated measurement technique is not required. The experimental results show that the proposed method can diagnose the degradation of a battery unit caused by

the internal shorts or opening of internal shorted in the discharging process.

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